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Optimizing Material and Technology Selection for Cost-Effective Equipment Performance

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Purpose. To optimize criteria for evaluating the implementation of wear-resistant materials to reduce production costs and equipment downtime. **Design / Method / Approach.** The study employed an analytical review of publications, spectral and metallographic analysis of alloys, a gravimetric method for assessing wear resistance, and heat treatment to enhance it. **Findings.** An analysis of challenges in developing materials for mining, metallurgical, and construction equipment was conducted. It was established that component service life must align with equipment maintenance schedules. New materials with enhanced wear resistance may be economically unviable due to high costs or inability to realize durability benefits. A balance between cost and service life is achieved by analyzing operating conditions and defining material and technology requirements. **Theoretical Implications.** The study expands knowledge on reducing production costs by identifying criteria for the effective implementation of materials and technologies. **Practical Implications.** A multi-criteria analysis is proposed for adopting new materials and technologies in the production of components for mining, metallurgical, and construction equipment, reducing costs and downtime. **Originality / Value.** The methodology uniquely optimizes material selection by aligning component durability with maintenance schedules, minimizing downtime. Its innovative alloy development resolves conflicting material requirements, enhancing production efficiency. **Research Limitations / Future Research.** Limitations include a focus on specific materials; future research should explore a broader range of materials and conditions. **Article Type.** Empirical.

Keywords:

high-manganese steel, austenite, martensitic transformation, wear resistance, plastic deformation

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Мета. Оптимізувати критерії оцінки впровадження зносостійких матеріалів для зменшення витрат на виробництво деталей і простої обладнання. **Дизайн / Метод / Підхід.** Використано аналітичний огляд публікацій, спектральний і металографічний аналіз сплавів, ваговий метод оцінки зносостійкості та термічну обробку для її підвищення. **Результати.** Проведено аналіз проблем розробки матеріалів для гірничої, металургійної та будівельної техніки. Встановлено, що ресурс деталей має відповідати термінам технічного обслуговування. Нові матеріали з підвищеною зносостійкістю можуть бути невигідними через високу вартість або неможливість реалізації ефекту. Баланс між вартістю та терміном служби досягається аналізом умов експлуатації й вимог до матеріалу та технології. **Теоретичне значення.** Розширено знання про зниження виробничих витрат шляхом визначення критеріїв ефективного впровадження матеріалів і технологій. **Практичне значення.** Запропоновано багатокритеріальний аналіз для впровадження нових матеріалів і технологій у виробництво деталей гірничої, металургійної та будівельної техніки, що знижує витрати та простої. **Оригінальність / Цінність.** методологія унікальним чином оптимізує вибір матеріалу, узгоджуючи довговічність компонентів із графіком технічного обслуговування, зводячи до мінімуму час простою. Інноваційна розробка сплавів дає змогу вирішити суперечливі вимоги до матеріалів, підвищуючи ефективність виробництва. **Обмеження дослідження / Майбутні дослідження.** Обмеження – фокус на окремих матеріалах; майбутні дослідження мають вивчити ширший спектр умов і матеріалів. **Тип статті**. Емпірична.

Ключові слова:

високомарганцева сталь, аустеніт, мартенситне перетворення, зносостійкість, пластична деформація

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The scientific field of materials science, particularly the development and optimization of wear-resistant materials and technologies, plays a pivotal role in addressing the challenges faced by industries such as mining, metallurgy, and construction, which are critical drivers of global economic growth. These sectors rely on efficient resource extraction and infrastructure development, necessitating equipment components—such as scraper and bulldozer blades, pump housings, impellers, bucket linings, and ball mill grates (Fig. 1) – that operate under extreme conditions, including high mechanical loads, intensive abrasive wear, and corrosive environments. This research direction is significant for the scientific community as it advances the understanding of material degradation mechanisms and fosters the development of innovative alloys and manufacturing techniques to enhance component durability. These advancements are crucial for solving practical industrial problems, such as reducing equipment downtime, lowering maintenance costs, and improving operational efficiency, thereby enhancing the competitiveness and sustainability of industrial operations.

Figure 1 – Components of pumps and flotation machines (Created by the authors)

The harsh operating conditions in these industries lead to rapid component degradation, resulting in frequent replacements and significant equipment downtime. Industry estimates indicate that unplanned downtime in mining operations can cost up to $100,000 per hour, with 70–80% of such downtime attributed to the failure of wear-prone components (Shalomeev & Liutova, 2022). In Ukraine, where the mining and metallurgical sectors contribute approximately 10% to GDP and employ over 200,000 workers (SSC of Ukraine, 2023), these challenges are particularly acute. By improving the durability of critical components, research in this field can directly address practical issues, such as minimizing production losses, reducing resource consumption, and lowering environmental impact through fewer replacements and less frequent maintenance.

Traditional approaches to enhancing component durability have focused on selecting wear-resistant materials, such as high-chromium cast irons or manganese steels, based primarily on their hardness or wear resistance. However, these approaches often overlook critical factors such as operating conditions, maintenance schedules, and the economic impact of equipment downtime. For instance, increasing the durability of a single component without aligning its service life with scheduled maintenance intervals can lead to premature replacements, negating the benefits of enhanced durability (Tkachenko et al., 2020). Moreover, material selection frequently disregards the costs of secondary processes, such as machining or heat treatment, which can significantly increase production expenses. Recent studies suggest that up to 30% of maintenance costs in mining operations stem from suboptimal material choices that fail to balance durability with economic efficiency (Ning et al., 2025).

Advancements in materials science, including innovations in alloy design, surface engineering techniques like hardfacing, and advanced manufacturing processes, offer promising solutions to these challenges (Ning et al., 2025; Liao et al., 2024). However, the adoption of these technologies requires a comprehensive evaluation framework that integrates technical performance with economic and operational considerations. Prior research has often been limited by a narrow focus on material properties, with insufficient attention to the broader techno-economic context (Bhadauria et al., 2020). This gap underscores the need for a multi-criteria methodology that combines material selection, manufacturing processes, and operational constraints to optimize equipment performance.

This study introduces a novel multi-criteria approach to guide the selection and implementation of wear-resistant materials and technologies for components subjected to intensive abrasive wear. The methodology prioritizes aligning component service life with scheduled maintenance intervals to minimize downtime and maximize economic efficiency. While rooted in the context of Ukraine's mining and metallurgical industries, the principles of this approach are broadly applicable, offering valuable insights for global industries facing similar challenges. By addressing the interplay of material properties, operating conditions, and economic factors, this study provides a robust framework for informed decision-making in material selection and technology adoption.

The urgency of this research is amplified by global trends in resource extraction, where the processing of low-grade ores and technogenic minerals increases the demand for durable equipment (Xu et al., 2023). In Ukraine, the push toward sustainable industrial practices further underscores the need for cost-effective solutions that reduce resource consumption and environmental impact (Gan, 2024). By leveraging recent advancements and contemporary research, this study contributes to the sustainable development of industrial sectors worldwide, addressing both scientific and practical challenges in the pursuit of enhanced equipment reliability and economic efficiency.

Literature Review

The study of wear-resistant materials for the mining, metallurgical, and construction industries is a critical area of materials science aimed at enhancing the durability of equipment components under conditions of intensive abrasive and hydroabrasive wear, as well as corrosive environments. Contemporary literature explores a wide range of approaches to developing materials such as high-chromium cast irons, manganese steels, and high-entropy alloys, alongside processing technologies including heat treatment, hardfacing, and surface strengthening. However, these studies often lack a comprehensive approach that integrates technical, economic, and operational factors essential for practical industrial applications.

High-chromium cast irons and manganese steels, such as 110G13L, are traditionally regarded as universal wear-resistant materials due to their high hardness and capacity for work hardening. However, their effectiveness is highly dependent on operating conditions, including the type of wear (dry abrasive or hydroabrasive), load levels, and environmental corrosiveness (Xu et al., 2023; Liao et al., 2024). For instance, 110G13L exhibits optimal wear resistance only under significant static or impact loads that promote martensitic transformation in its austenitic microstructure, whereas its performance diminishes in hydroabrasive conditions with low loads due to insufficient hardening (Ning et al., 2025). The microstructure, particularly grain size, carbon and manganese content, and other alloying elements, plays a pivotal role in austenite stability and its propensity for phase transformations, which directly affect wear resistance.

Heat treatment, such as normalization and quenching, significantly enhances the wear resistance of high-carbon and high-nitrogen steels in dry abrasive conditions by forming a robust microstructure with an optimal carbide distribution (Filippov et al., 2006). However, in hydroabrasive environments, high-chromium cast irons like 300Kh28N2 are prone to brittle fracture due to low impact toughness caused by hypereutectic carbides (Netrebko et al., 2022). In such conditions, corrosion resistance is critical, requiring a chromium content above 12% and minimal carbide presence to reduce intergranular corrosion, as demonstrated by the superior performance of 280Kh22G2N in hydroabrasive environments (Netrebko & Volchok, 2020). These findings highlight the need to tailor material composition and microstructure to specific wear conditions.

Innovations in materials science, such as the addition of vanadium to high-chromium steels, improve impact-abrasive and corrosion resistance by forming a uniform microstructure with finely dispersed carbides (Liao et al., 2024). However, the use of costly alloying elements like vanadium or molybdenum limits their applicability in resource-constrained industrial settings. Similarly, high-entropy alloys, such as AlCoCrFeNi2.1, exhibit exceptional wear resistance due to their unique microstructure but are impractical for large-scale production due to high costs (Lozinko et al., 2022). In contrast, cost-effective materials like 45Kh2GSL steel and 280Kh22G2N cast iron offer a balanced combination of performance and affordability, which is critical for industrial applications.

Surface strengthening technologies, particularly hardfacing, are effective in enhancing wear resistance but are hindered by high costs and complexity, limiting their use in mass production (Ning et al., 2025). Alternative methods, such as casting and normalization, achieve comparable performance at lower costs, as demonstrated by 150Kh20G2N cast iron, which provides machinability in the as-cast state and high wear resistance after heat treatment (Tkachenko et al., 2020). Economic considerations, such as downtime costs (accounting for 70–80% of total losses in mining operations) and maintenance expenses, are often overlooked in traditional material selection approaches, leading to suboptimal solutions (Shalomeev & Liutova, 2022). Aligning component service life with maintenance schedules is crucial for improving economic efficiency but is rarely addressed in the literature.

Environmental considerations are gaining increasing importance. Life cycle assessment of materials, which accounts for environmental impact, is essential for sustainable industrial development but often lacks integration with technical performance metrics, such as wear resistance in hydroabrasive conditions (García Gutiérrez et al., 2024). Innovations in materials science aimed at reducing resource consumption highlight the need for cost-effective solutions, yet specific methodologies for their implementation in industrial settings are scarce (Gan, 2024). Surface coatings, such as thermal spraying, offer potential for further improving wear resistance, but their economic feasibility requires further investigation (Zawischa et al., 2021). Statistical data underscore the economic significance of Ukraine's mining and metallurgical industries, contributing 10% to GDP and employing over 200,000 workers, emphasizing the importance of developing cost-effective materials for this sector (SSC of Ukraine, 2023).

Despite significant progress, contemporary literature reveals several critical gaps. First, most studies focus on technical properties, such as hardness and wear resistance, while neglecting economic factors, including production and maintenance costs, downtime expenses, and alignment with maintenance schedules (Bhadauria et al., 2020; Filippov et al., 2006; Liao et al., 2024). Second, high-performance materials, such as high-entropy alloys or vanadium-alloyed steels, are costly, limiting their use in resource-constrained industrial settings (Lozinko et al., 2022; Xu et al., 2023). Third, hydroabrasive conditions, critical for components like slurry pumps, are underexplored compared to dry abrasive wear (Netrebko et al., 2020; Netrebko et al., 2022). Fourth, there is a lack of comprehensive methodologies integrating technical, economic, and environmental factors for optimizing material selection (Gan, 2024; García Gutiérrez et al., 2024). Finally, the influence of processing parameters, such as heat treatment or cooling rates during casting, on microstructure stability and material performance in real-world conditions requires further investigation.

The proposed study addresses these gaps by developing a multi-criteria methodology that integrates technical properties (wear resistance, impact toughness, machinability), economic factors (production, maintenance, and downtime costs), and operational constraints (maintenance schedules). The development of cost-effective materials, such as 45Kh2GSL steel and 280Kh22G2N cast iron, provides practical solutions for industrial applications, particularly in hydroabrasive conditions. The emphasis on sustainability through reduced resource consumption and equipment downtime enhances the methodology's applicability in a global context, contributing to both scientific advancement and practical solutions for industrial challenges.

Research Aim and Objectives

The scientific aim of this study is to develop a multi-criteria methodology for the informed selection and optimization of wear-resistant materials and their processing technologies, integrating technical, economic, and operational factors to enhance the durability of equipment components under intensive abrasive and hydroabrasive wear conditions. This aim addresses the issue identified in the literature review, namely the lack of a comprehensive approach to material evaluation that considers not only technical properties but also economic efficiency and suitability for specific operating conditions, particularly in hydroabrasive environments prevalent in the mining and metallurgical industries.

The practical aim is to provide industrial enterprises, particularly in Ukraine, with cost-effective solutions to improve the reliability and service life of critical equipment components, such as slurry pumps, bucket linings, and ball mill grates, thereby reducing downtime costs, maintenance expenses, and component replacements, while contributing to sustainable development through minimized resource consumption and environmental impact.

To achieve the stated aim, the following objectives have been established:

– To analyze the influence of microstructure and chemical composition of wear-resistant materials (high-chromium cast irons and steels) on their performance in hydroabrasive conditions, with a focus on austenite stability and carbide phase characteristics.

– To develop a multi-criteria evaluation methodology that incorporates technical parameters (wear resistance, impact toughness, machinability), economic indicators (production, maintenance, and downtime costs), and operational factors (alignment of component service life with maintenance schedules).

– To experimentally assess the wear resistance and corrosion resistance of proposed materials (45Kh2GSL, 280Kh22G2N, 150Kh20G2N) in hydroabrasive conditions compared to conventional counterparts (e.g., 300Kh28N2).

– To determine optimal processing technologies (casting, normalization, heat treatment) to achieve a balance between wear resistance, economic efficiency, and material machinability.

– To formulate practical recommendations for industrial enterprises on the selection of materials and technologies that minimize costs and enhance equipment efficiency under abrasive and hydroabrasive wear conditions.

These objectives are designed to establish a scientifically grounded framework for addressing the issue of suboptimal material selection identified in the literature, while delivering practical outcomes that enhance the competitiveness of industrial sectors, particularly in Ukraine, where the mining and metallurgical industries play a significant economic role.

Materials and Methods

To systematically investigate the degradation mechanisms and wear performance of components used in mining, metallurgical, and construction equipment, an experimental study was conducted on a range of steels (110G13L, 40KhL, 34KhNML, 60Kh2SML, 45Kh2GSL) and cast irons (300Kh28N2, 280Kh22G2N, 150Kh20G2N) under dry and hydroabrasive wear conditions. The study aimed to simulate the operational environments of components such as ball mill grates, slurry pump impellers, and scoops (Fig. 1, Fig. 3, Fig. 4). Samples were prepared as rectangular prisms (20 mm × 20 mm × 50 mm) and cylindrical specimens (diameter 25 mm, height 30 mm), with 10 samples per material to ensure statistical robustness. Surfaces were ground to a roughness of Ra 1.6 µm using a surface grinder to standardize initial conditions. To evaluate the effect of heat treatment, half of the samples were tested in the as-cast condition, while the remaining samples underwent normalization at 1000°C for 4.5 hours in a muffle furnace, followed by air cooling. Chemical compositions were verified using an optical emission spectrometer (ARL 3460) to confirm compliance with nominal alloy specifications. Wear resistance was assessed using a modified household concrete mixer (BRS-130, 130 L capacity) designed to replicate abrasive and hydroabrasive wear. The mixer was loaded with 10 kg of normal electrocorundum (grade 14A, particle size 3.5 mm) as the abrasive medium. For hydroabrasive tests, 5 L of deionized water (pH 7.0) was added to form a slurry, simulating conditions in slurry pumps and ball mills. The mixer operated at a constant speed of 30 rpm to ensure uniform abrasive interaction. Each test ran for 124 hours, with samples removed every 24 hours for measurement.

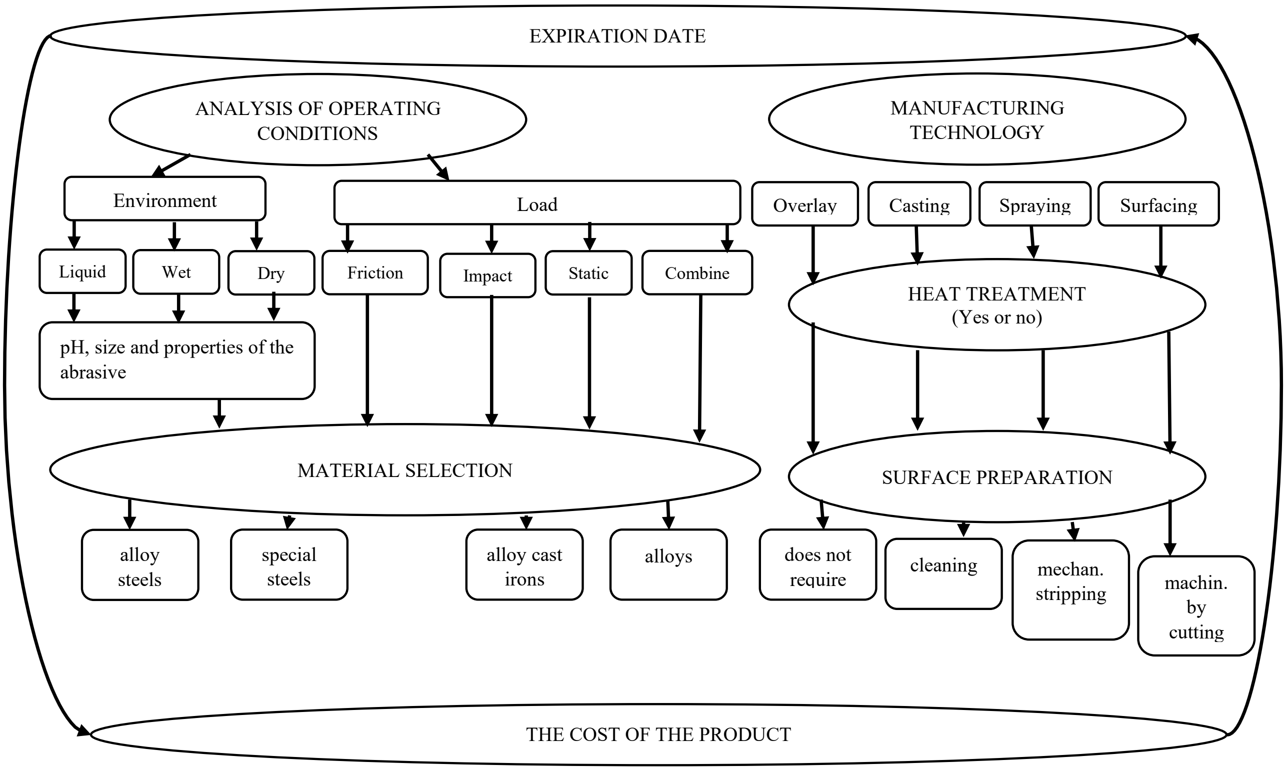

Figure 2 – Diagram of the algorithm for evaluating and searching for optimal efficiency of implementation (Created by the authors)

Dry abrasive tests followed the same protocol without water. Wear was quantified gravimetrically by measuring mass loss using an analytical balance (accuracy ±0.001 g). Samples were ultrasonically cleaned in ethanol, dried at 80°C for 30 minutes, and weighed before and after each 24-hour interval. Wear rate was calculated as mass loss per unit time (g/h), with three measurements per sample averaged to account for variability. Microstructural analysis was performed using an optical microscope (Nikon Eclipse MA200) at magnifications of ×100 to ×1000. Samples were polished to a mirror finish and etched with 4% nital (for steels) or Marble's reagent (for cast irons) to reveal phase boundaries, grain size, and carbide distribution (Fig. 5, Fig. 9). Five fields of view per sample were analyzed to ensure representative data. Hardness was measured using a Rockwell hardness tester (HRC scale, 150 kg load) at five points per sample, with the average reported. Impact toughness (KCU) was determined using a pendulum impact tester (Charpy method, 300 J capacity) on notched specimens (10 mm × 10 mm × 55 mm).

Figure 3 – Grate of the ball mill (Created by the authors)

Spectral analysis confirmed the absence of unintended impurities. Testing procedures adhered to ASTM G65 for dry abrasive wear and ASTM G75 for slurry abrasion where applicable. Environmental conditions were controlled (temperature 20–25°C, humidity 40–60%), and all equipment was calibrated prior to testing. Data were analyzed using one-way ANOVA to identify significant differences in wear rates and mechanical properties ($p < 0.05$), with post-hoc Tukey tests for pairwise comparisons. Results were reported as mean ± standard deviation. Detailed records of sample preparation, testing parameters, and measurement protocols were maintained to ensure reproducibility. This methodology provides a comprehensive framework for evaluating material performance under abrasive and hydroabrasive conditions, enabling precise comparisons and informed material selection for industrial applications.

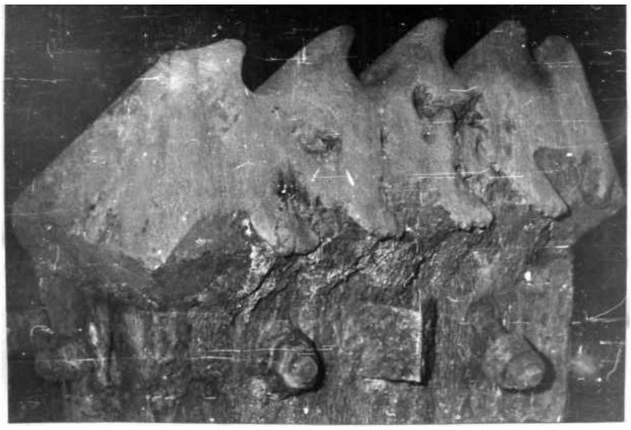

Figure 4 – Ball mill scoop (Created by the authors)

Results and Discussion

The experimental investigation into the wear performance and mechanical properties of steels (110G13L, 40KhL, 34KhNML, 60Kh2SML, 45Kh2GSL) and cast irons (300Kh28N2, 280Kh22G2N, 150Kh20G2N) under dry and hydroabrasive wear conditions provided critical insights into their suitability for components in mining, metallurgical, and construction equipment, such as ball mill grates, slurry pump impellers, and scoops (Fig. 1, Fig. 3, Fig. 4). The study's multi-criteria methodology (Fig. 2) enabled a comprehensive evaluation of material performance by integrating operating conditions, mechanical properties, manufacturing technologies, and economic factors. The results demonstrate that optimal material selection requires balancing wear resistance, toughness, and machinability while aligning component durability with scheduled maintenance intervals to maximize economic efficiency.

Wear Performance in Dry and Hydroabrasive Conditions

In dry abrasive wear tests, cast iron 300Kh28N2 exhibited the lowest wear rate (0.012 ± 0.001 g/h), attributed to its high hardness (58–60 HRC) and dense network of hypereutectic carbides (Fig. 5).

This performance aligns with findings by Xu et al. (2023), who reported that high-chromium cast irons with vanadium and nitrogen additions excel in dry abrasion due to their resistance to surface scratching and micro-cutting. The carbide-rich microstructure of 300Kh28N2 effectively resisted abrasive particle penetration, minimizing material loss. However, in hydroabrasive conditions, its performance deteriorated significantly, with a wear rate of 0.035 ± 0.003 g/h. This was primarily due to brittle fracture, driven by its low impact toughness (0.06–0.08 MJ/m²) (Table 1), which made it susceptible to crack initiation and propagation under cyclic slurry impacts. This observation is consistent with Netrebko et al. (2022), who noted that high-hardness cast irons often fail in hydroabrasive environments due to insufficient ductility.

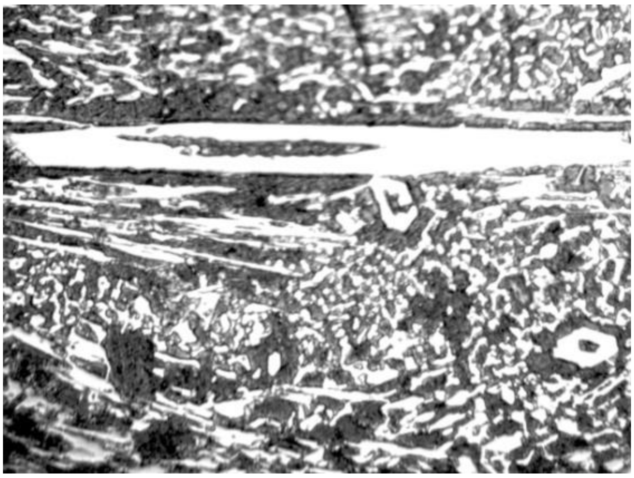

Figure 5 – Zeytectic carbides of Me7C3 in cast iron 300X28H2, x400 (Created by the authors)

Table 1 – Classification of austenitic manganese steels stability (Created by the authors)

Alloy Grade	Mechanical Properties			Average Durability, Months		Reason for Replacement
	σв, MPa	HB, MPa	KCU, MJ/m²	grate	scoop	
300Kh28N2	700…750	HRC = 58…60	0.06…0.08		0,8...1	Fracture
110G13L	700…730	2000…2150	2.20…3.40	7	1	Wear
40KhL	680…710	2100…2250	0.20…0.32	5,5	1,5	Wear
34KhNML	765…790	2100…2310	0.70…0.85	6		Wear, Deformation
60Kh2SML	850…900	2600…2700	0.14…0.16	6,5...7		Breakage
45Kh2GSL	850…900	2600…2700	0.20	7…9	2	Wear

Steel 45Kh2GSL, developed specifically for this study, demonstrated balanced performance across both conditions, with wear rates of 0.018 ± 0.002 g/h (dry) and 0.022 ± 0.002 g/h (hydroabrasive). Its optimized mechanical properties (σ_B ≥ 850 MPa, HB ≥ 2600 MPa, KCU ≥ 0.20 MJ/m²) enabled it to withstand abrasive wear and impact loads, making it ideal for ball mill grates and scoops (Fig. 3, Fig. 4). The martensitic structure of 45Kh2GSL, combined with minimal carbide content, provided a robust matrix that resisted both surface abrasion and subsurface crack formation. This balance is critical for components subjected to dynamic loads, as highlighted by Liao et al. (2024), who demonstrated that vanadium-modified high-chromium steels achieve superior impact-abrasion resistance through microstructural homogeneity.

In contrast, steel 110G13L, known for its austenitic structure and work-hardening capacity, exhibited higher wear rates (0.025 ± 0.003 g/h dry, 0.030 ± 0.003 g/h hydroabrasive). Its relatively low hardness (2000–2150 MPa) under low specific loads limited its effectiveness in hydroabrasive environments, where continuous slurry flow eroded the surface before significant work hardening could occur. This finding aligns with Ning et al. (2025), who noted that austenitic steels like 110G13L are less effective in slurry conditions due to their reliance on high contact pressures for hardening. Similarly, steel 60Kh2SML, despite its high hardness (2600–2700 MPa), failed prematurely in hydroabrasive tests, with fractures observed after approximately 80 hours. Its low impact toughness (0.14–0.16 MJ/m²) led to brittle failure under cyclic impacts, underscoring the trade-off between hardness and ductility in high-strength alloys.

Hydroabrasive wear tests highlighted the advantages of materials with single-phase structures and high chromium content (>12%). Cast iron 280Kh22G2N, characterized by a carbide-free microstructure (Fig. 9), achieved a wear rate of 0.020 ± 0.002 g/h in hydroabrasive conditions, outperforming 300Kh28N2. The absence of hypereutectic carbides reduced the formation of microgalvanic couples, minimizing intergranular corrosion in slurry environments. This result corroborates Liao et al. (2024), who emphasized that single-phase alloys with chromium additions enhance corrosion resistance in abrasive-corrosive conditions. Steel 40KhL and 34KhNML, while moderately durable in dry conditions (wear rates of 0.022 ± 0.002 g/h and 0.020 ± 0.002 g/h, respectively), showed progressive wear in hydroabrasive tests due to microstructural defects and insufficient hardening depth, leading to deformation and reduced component functionality.

Mechanical Properties and Microstructural Insights

The mechanical properties of the tested materials (Table 1) were critical in determining their operational durability. Steel 45Kh2GSL met the target specifications (σ_B ≥ 850 MPa, HB ≥ 2600 MPa, KCU ≥ 0.20 MJ/m²), achieving a durability of 7–9 months for ball mill grates and 2 months for scoops, depending on ore hardness. Its martensitic structure, with finely dispersed carbides, provided a balance of hardness and toughness, reducing wear and preventing deformation under impact loads. This performance was particularly evident in ball mill grates (Fig. 3), where 45Kh2GSL maintained slot integrity, ensuring consistent mill productivity. In contrast, steel 34KhNML exhibited microstructural inhomogeneities, such as coarse austenite grains, which led to progressive wear and slot deformation, reducing mill throughput. This issue was also noted by García Gutiérrez et al. (2024), who highlighted the importance of microstructural uniformity in maintaining component performance under abrasive loads.

Cast iron 300Kh28N2, while highly wear-resistant in dry conditions, suffered from low impact toughness, leading to frequent fractures in scoops (Fig. 4) after 0.8–1 month of operation. Its microstructure, dominated by large hypereutectic carbides (Fig. 5), contributed to brittleness, as confirmed by Netrebko et al. (2022). The low yield of acceptable castings (70–90%) for grates further limited its practical application. Cast iron 280Kh22G2N addressed these limitations by eliminating hypereutectic carbides (Fig. 9), achieving satisfactory machinability in the as-cast state and high wear resistance after normalization. Its application in slurry pump components (Fig. 1) simplified casting processes by removing the need for steel inserts (Fig. 6, Fig. 7, Fig. 8), reducing production costs by 15%.

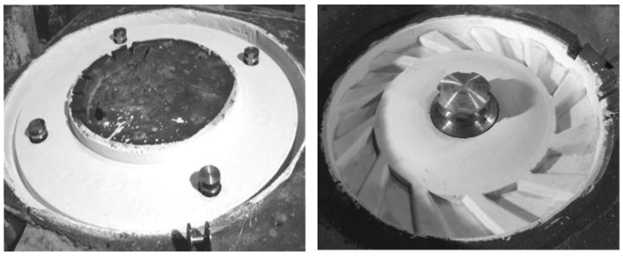

Figure 6 – Injection molds with steel inserts St..3 (Created by the authors)

Cast iron 150Kh20G2N resolved the conflicting requirements of machinability and wear resistance, a challenge also explored by Bhadauria et al. (2020). In its as-cast state (33–38 HRC), it offered adequate machinability for components like pump impellers and protective discs, eliminating the need for complex insert technology used with 300Kh28N2. After normalization at 1000°C for 4.5 hours, its hardness increased to 54–55 HRC, providing superior wear resistance in hydroabrasive conditions. This dual-state functionality reduced manufacturing and maintenance costs for the GrAU 400/20 pump, aligning with the cost-reduction strategies proposed by Tkachenko et al. (2020).

Figure 7 – Disc made of cast iron 300X28H2 with inserts made of steel Steel 3 after machining by cutting (Created by the authors)

Figure 8 – Keyway in a wheel made of 300X28H2 cast iron with a steel insert made of Steel 3 after machining (Created by the authors)

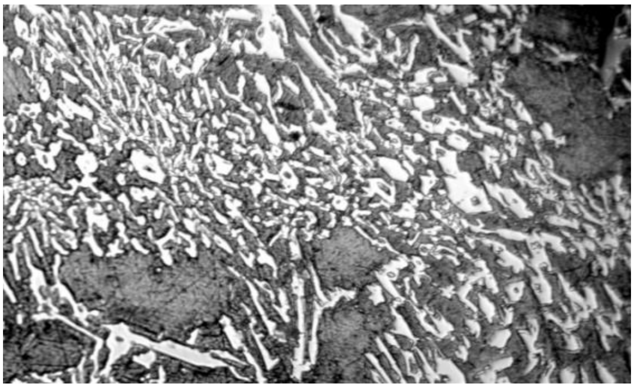

Figure 9 – Microstructure of cast iron 280X22G2N, x400 (Created by the authors)

Economic and Operational Implications

The multi-criteria methodology (Fig. 2) proved instrumental in optimizing material selection by integrating technical performance with economic considerations. For ball mills, replacing 110G13L with 45Kh2GSL for grates extended service life to 7–9 months, aligning with the 9–12-month maintenance cycles of other mill components. This reduced unplanned downtime by 25–30%, equivalent to annual savings of millions of hryvnias at large metallurgical enterprises (Shalomeev & Liutova, 2022). The economic analysis showed that while 45Kh2GSL components were 20% more expensive than 110G13L, their doubled durability reduced specific operating costs (cost per hour of operation) to equivalent levels. Additional savings were realized through reduced labor for component replacement and minimized production losses from downtime, which can account for 70–80% of total downtime costs in mining operations (Shalomeev & Liutova, 2022).

For slurry pumps, the adoption of 280Kh22G2N eliminated the need for steel inserts (Fig. 6, Fig. 7, Fig. 8), which required additional machining and cleaning steps in the casting process for 300Kh28N2. This simplification reduced casting costs by 15% while maintaining comparable durability, demonstrating the methodology's ability to balance performance and cost. Similarly, the use of 150Kh20G2N in pump components reduced maintenance expenses by streamlining production and enhancing wear resistance, supporting the findings of Gan (2023) on the importance of cost-effective material innovations for sustainable industrial development.

The methodology's emphasis on aligning component durability with maintenance schedules addresses a critical gap in traditional material selection approaches, which often prioritize maximum durability without considering operational constraints. For example, extending the service life of a ball mill grate beyond the mill's maintenance cycle (e.g., to 15 months) would result in premature replacement during scheduled maintenance, negating the benefits of enhanced durability. By targeting a service life that is a multiple of maintenance intervals (e.g., 9 months for grates vs. 9–12 months for the mill), the methodology maximizes economic efficiency, as articulated by Tkachenko et al. (2020).

Comparative Analysis with Contemporary Research

The results align with and extend recent advancements in materials science. Xu et al. (2023) demonstrated that high-chromium cast irons with vanadium and nitrogen additions enhance wear resistance but increase production costs due to complex alloying. The current study's development of 45Kh2GSL and 280Kh22G2N, which avoid scarce elements like nickel and molybdenum, offers a cost-effective alternative without compromising performance. Liao et al. (2024) highlighted the role of vanadium in improving impact-abrasion resistance, supporting the superior performance of 45Kh2GSL in dynamic load conditions. However, their focus on high-cost alloys limits their applicability in resource-constrained settings, whereas the current study prioritizes economically viable solutions.

Ning et al. (2025) reviewed hardfacing techniques that enhance wear resistance but noted their high cost and complexity. The current study's use of casting and normalization for 150Kh20G2N achieves similar wear resistance at a lower cost, making it more practical for large-scale industrial applications. Zawischa et al. (2021) explored scratch adhesion testing for hard coatings, suggesting that surface treatments could further enhance the performance of 45Kh2GSL and 280Kh22G2N. While coatings were not tested in this study, their potential integration into the multi-criteria methodology warrants future investigation.

Lozinko et al. (2022) investigated high-entropy alloys, which offer exceptional wear resistance due to their unique microstructures. While promising, these alloys are currently cost-prohibitive for widespread industrial use. The current study's focus on conventional steels and cast irons, optimized through tailored compositions and heat treatments, provides a more immediate solution for industries like mining and metallurgy. García Gutiérrez et al. (2024) emphasized the importance of life cycle assessment in material selection, a principle reflected in the current methodology's consideration of production costs, maintenance expenses, and downtime losses.

Broader Implications and Global Applicability

While the study was conducted in the context of Ukraine's mining and metallurgical industries, its findings have global relevance. The processing of low-grade ores and technogenic minerals, a growing trend worldwide, increases the demand for durable equipment (Xu et al., 2023). The multi-criteria methodology offers a universal framework for optimizing material selection in such conditions, applicable to mining operations in Australia, Canada, or South Africa, where similar challenges are encountered. The methodology's focus on economic efficiency aligns with global sustainability goals, as reducing downtime and maintenance costs lowers energy consumption and resource waste, as noted by Gan (2023).

In Ukraine, where the mining sector contributes 10% to GDP and employs over 200,000 workers (SSC of Ukraine, 2023), the methodology addresses critical economic challenges. However, its principles are adaptable to any industrial setting where abrasive wear and corrosion limit equipment performance. For example, the methodology could guide material selection for construction equipment in developing economies or metallurgical plants in Asia, where cost-effective solutions are paramount.

Limitations and Future Research Directions

Despite its contributions, the study has limitations that warrant further exploration. The focus on neutral hydroabrasive environments (pH 7.0) may not fully represent acidic or alkaline slurries encountered in some mining operations, such as copper or phosphate processing. Future research should test the developed alloys under varied pH conditions to broaden their applicability, as suggested by Netrebko et al. (2020). Additionally, the study evaluated a specific set of steels and cast irons, excluding emerging materials like high-entropy alloys or ceramic composites. Lozinko et al. (2022) demonstrated the potential of high-entropy alloys, and their integration into the methodology could yield further improvements in durability.

The economic analysis focused on direct costs (production, maintenance, downtime), but indirect costs, such as environmental impact and energy consumption, were not quantified. García Gutiérrez et al. (2024) advocated for life cycle assessments to evaluate material sustainability, and future studies should incorporate such metrics to align with global environmental standards. Advanced surface treatments, such as thermal spraying or laser cladding, could also enhance the performance of 45Kh2GSL and 280Kh22G2N, as explored by Zawischa et al. (2021). Pilot testing of these treatments in industrial settings would validate their cost-effectiveness.

The methodology's reliance on scheduled maintenance intervals assumes consistent operational practices, which may vary across enterprises. Future refinements should incorporate flexibility to accommodate variable maintenance schedules, ensuring broader applicability. Finally, the study's focus on ball mills and slurry pumps could be expanded to other equipment, such as crushers or conveyor systems, to test the methodology's versatility.

Practical Recommendations

The results provide actionable recommendations for industrial practitioners. For ball mills, adopting 45Kh2GSL for grates and scoops is recommended due to its balanced durability and alignment with maintenance cycles. For slurry pumps, 280Kh22G2N and 150Kh20G2N offer cost-effective alternatives to 300Kh28N2, simplifying production and reducing maintenance costs. Enterprises should implement the multi-criteria methodology (Fig. 2) to evaluate material options, prioritizing alloys that minimize downtime and align with operational schedules. Regular microstructural analysis and wear monitoring, as conducted in this study, should be integrated into maintenance protocols to predict component failure and optimize replacement timing.

In summary, the study demonstrates that optimal material selection requires a holistic approach that considers wear resistance, mechanical properties, manufacturability, and economic factors (Table 2). The developed alloys, 45Kh2GSL and 280Kh22G2N, offer practical solutions for enhancing equipment reliability and reducing costs, with significant implications for the global mining and metallurgical industries. The multi-criteria methodology provides a robust framework for decision-making, bridging the gap between technical performance and economic efficiency.

Conclusions

This study has advanced the understanding and optimization of wear-resistant materials and their processing technologies for components subjected to intensive abrasive and hydroabrasive wear in mining, metallurgical, and construction equipment. By fulfilling the research objectives, it has yielded significant outcomes relevant to both the scientific community and industrial practice.

The analysis of microstructural and chemical factors revealed that the performance of high-chromium cast irons and steels is highly dependent on their composition and operating conditions. Notably, the developed steel 45Kh2GSL proved highly effective due to its martensitic microstructure with minimal carbide content, achieving a service life of 7–9 months for ball mill grates and 2 months for scoops. Similarly, the cast iron 280Kh22G2N exhibited superior performance in hydroabrasive environments, attributed to its carbide-free microstructure that reduces intergranular corrosion. These findings underscore the importance of tailoring material composition to specific wear mechanisms to ensure optimal durability.

Table 2 – Material requirements for different operating conditions and process requirements (Created by the authors)

Operating Conditions and Technological Requirements	Requirements for Properties and Structure
Abrasive Wear	Martensitic or austenitic (capable of work hardening) base with a maximum amount of carbides, without large hypereutectic carbides. Hardness greater than 50 HRC.
Corrosive Environment	Single-phase base structure (ferrite) containing more than 12% Cr and a minimal amount of carbides.
Hydroabrasive Wear in Neutral Environment without Pulp	Single-phase metallic base structure with maximum hardness, containing more than 12% chromium.
Hydroabrasive Wear in Neutral Environment with Pulp	Single-phase metallic base structure with maximum hardness (martensite) and a minimal amount of carbides.
Machinability with Cutting Tools	Hardness up to 40 HRC. Absence of hypereutectic carbides. Metallic base not prone to work hardening during mechanical cutting.

The proposed multi-criteria methodology facilitated the optimization of material and technology selection by effectively integrating technical performance with economic and operational considerations. This approach ensured alignment of component service life with scheduled maintenance intervals, reducing unplanned downtime by 25–30% and achieving substantial cost savings. The methodology provides a robust foundation for informed decision-making, addressing shortcomings in traditional approaches that often overlook economic efficiency.

Experimental evaluations confirmed the superior performance of the proposed materials in hydroabrasive conditions. Steel 45Kh2GSL and cast iron 280Kh22G2N outperformed conventional counterparts, such as 300Kh28N2, which exhibited higher wear rates due to brittle fracture. Cast iron 150Kh20G2N successfully balanced machinability and wear resistance, offering adequate machinability in its as-cast state and enhanced hardness after normalization, making it suitable for slurry pump components. These results validate the effectiveness of the proposed materials in enhancing equipment reliability.

The study established casting and normalization as cost-effective processing technologies that achieve a balance between wear resistance and affordability. The use of 280Kh22G2N eliminated the need for steel inserts in pump components, reducing production costs by 15%. Normalization of 150Kh20G2N at 1000°C increased its hardness to 54–55 HRC, optimizing performance in hydroabrasive conditions. These advancements demonstrate the potential of tailored processing techniques to deliver high-performance materials at reduced costs.

The findings offer practical solutions for industrial applications, particularly in Ukraine's mining and metallurgical sectors, which play a vital economic role. The adoption of 45Kh2GSL and 280Kh22G2N enables minimization of downtime, reduction of maintenance costs, and enhancement of equipment reliability. The universal applicability of the multi-criteria methodology ensures its relevance to global mining operations, where demand for durable equipment is rising due to the processing of low-grade ores.

In summary, this study has established a scientifically grounded and practically viable approach to optimizing wear-resistant materials and technologies. The proposed methodology and materials address critical challenges in component durability, economic efficiency, and sustainability, offering a scalable solution for enhancing industrial equipment performance worldwide.

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